A Laboratory Study of the Effects of Compaction on the Volumetric and Rutting Properties of CRM Asphalt Mixtures

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ABSTRACT

The compaction conditions (e.g., compaction temperature and compaction level) of crumb rubber modifier (CRM) asphalt mixtures should be determined carefully because the viscosity and amount of the CRM binder affects the compactability of the mixtures. Furthermore, the properties of CRM mixtures relating to the compaction conditions have not been studied in detail. In this study, a laboratory investigation was conducted on the volumetric and rutting properties of CRM mixtures as a function of compaction conditions. For this research work, four Superpave mix designs for four different asphalt binders (control, SBS-modified, 10% rubber modified, and 15% rubber modified) were carried out to determine the optimum asphalt contents. A total of 260 specimens were fabricated using the Superpave gyratory compactor at four compaction temperatures (116, 135, 154, and 173°C) and five compaction levels (20, 40, 60, 80, and 100 gyrations). The volumetric properties were obtained and analyzed, and the rutting resistance of the mixtures was measured using the Asphalt Pavement Analyzer (APA). The results from this study indicated that 1) the compaction temperatures used in this study significantly affected the volumetric properties of the CRM mixtures, unlike the control and SBS-modified mixtures; 2) in general, the air void contents of the mixtures were significantly influenced by the compaction levels; 3) the higher air void contents of the CRM mixtures seemed to have a detrimental effect on the rutting resistance.

Keywords: asphalt, crumb rubber, compaction, volumetric properties, rutting

INTRODUCTION

Background

In the United States, approximately 300 million scrap tires are generated each year and the same amount is produced in Europe (Amirkhanian and Corley 2004*)*. In addition, in many Asian countries, this has been a serious issue due to many reasons (e.g., lack of landfill space, environmental issues, etc.). There are many applications in the civil engineering area that scrap tires could be utilized to enhance the properties of the existing materials. For instance, crumb rubber modifier (CRM) can be used to produce asphalt pavements that exhibit increased pavement life, resistance to cracking, decreased traffic noise, reduced maintenance costs and resistance to rutting (Ruth and Roque 1995, Liang and Lee 1996, Huang et al. 2002). At present, more and more countries have begun using CRM mixtures due to these advantages.

Compaction is the process by which the volume of air in an asphalt mixture is reduced through the application of external forces. The expulsion of air enables the mix to occupy a smaller space thereby increasing the unit weight or density of the mix. Compaction is an essential factor in the design and subsequent production of asphalt mixtures (Hot Mix Asphalt Materials 1996). The compaction conditions such as compaction temperature and level influences workability and finishability, which are related to achieving the proper density of the mixture.

Under Superpave specifications, the compaction temperature for conventional asphalt mixtures is defined as the range of temperatures where an unaged binder has a kinematic viscosity of $280 \pm 30 mm^2/s$, and compactive effort is based on a function of traffic level (Superpave 2003, ASTM D 2493). However, these requirements were determined based on experience with unmodified asphalt binders. In terms of CRM mixtures, the compaction conditions need to be determined carefully because the viscosity and amount of the CRM binder affect the compactability of the mixtures. Based on the experience in the field, CRM mixtures are compacted at a higher temperature than unmodified mixtures (Amirkhanian and Corley 2004*)*. However, the properties of the CRM mixtures depending on compaction temperature and level is considered to be somewhat unclear and few studies have been done in this area.

Research Objective and Scope

This study investigated the properties of CRM asphalt mixtures as a function of compaction conditions, such as compaction temperature and compaction level, using the Superpave Gyratory Compactor (SGC). Four mixtures including control (PG 64-22), 3% SBS-modified PG 76-22, 10% rubber-modified and 15% rubber-modified binders were designed using Superpave specifications. The mixtures used for investigating the compaction temperature were compacted at four temperatures of 116, 135, 154, and 173°C using two compaction levels of 30 and 70 gyrations. In addition, the mixtures used for determining the effects of compaction levels were compacted using five compaction levels of 20, 40, 60, 80, and 100 gyrations at 154°C. The volumetric and rutting properties of these mixtures were evaluated.

MATERIALS AND TEST PROGRAM

Materials

Four binders (control PG 64-22, 3% SBS-modified PG 76-22, 10% and 15% rubber-modified binders) were used in this study. The control and 3% SBS-modified binders were collected from one source. One type of rubber, which was produced by mechanical shredding at ambient temperature, was used with a gradation as shown in Table 1. To ensure that the consistency of the rubber was maintained throughout the study, only one batch of crumb rubber was used in this study. Rubber-modified binders were made by adding a specified amount of rubber (-40 mesh) to the control binder, mixing with a stirrer (700 rpm) at 177°C for 30 minutes (Shen et al. 2005). This mixing condition matches the field practices used in South Carolina to produce field CRM mixtures. The properties of all the binders are listed in Table 2. One granite aggregate source was used for preparing samples (Table 3). Hydrated lime, used as an anti-strip additive, was added at a rate of 1% by dry mass of aggregate. The experimental flow chart of this study and test combinations are shown in Figure 1.

Superpave Mix Designs

A nominal maximum size 9.5mm Superpave mixture was used for the mix design in this study. The procedures described in AASHTO T 312 regarding the preparation of HMA specimens were followed. All mixtures used an identical aggregate structure to distinguish the influence of the binders (Figure 2). Optimum asphalt contents were obtained and used to produce specimens at four different compaction temperatures and five different compaction levels (gyration numbers in SGC).

Compaction as a function of temperature in SGC

The mixing of the aggregates with the asphalt binders was conducted at temperatures determined using a plot of viscosity versus temperature. The loose asphalt-aggregate mixtures were oven aged at the compaction temperatures for 2 hours prior to the compaction. The four compaction temperatures used were 116, 135, 154, and 173°C. This range was selected based on the temperatures (135 and 154°C) which are commonly used as short-term oven aging temperatures in the laboratory to simulate binder aging and absorption during the construction of HMA pavements (Superpave 2003).

The specimens were fabricated to the two target air void contents of 7±1% and 4±1% using 30 and 70 gyrations of SGC, respectively. Each specimen was 150 mm in diameter and

100±5 mm in height. A total of 160 specimens (4 binders * 4 compaction temperatures * 2 gyration levels * 6 (for 30 gyrations) or 4 repetitions (for 70 gyrations)) were prepared and tested.

Compaction as a function of gyration level in SGC

The same mixing condition used for compaction as a function of temperature was utilized and the loose mixtures were oven aged at 154°C for 2 hours prior to the compaction. The compaction was carried out as a function of gyration level. The five compaction levels in SGC used were 20, 40, 60, 80, and 100 gyrations. This range was chosen to produce the target air void contents from 2±1% to 8±1%. A total of 100 specimens (4 binders * 5 compaction levels * 5 repetitions) were prepared and tested.

Asphalt Pavement Analyzer (APA)

After the air void contents were measured, the specimens were cut to a height of 75mm using a diamond tipped saw blade. The APA test in this study was conducted on cylindrical samples with a height of 75 mm and diameter of 150 mm. The test temperature was 64°C, the hose pressure was 690kPa, and the wheel load was 445N. The rut depth was recorded and measured manually after 8,000 cycles.

Analysis Method

Statistical analysis was performed using the Statistical Analysis System (SAS) program to conduct analysis of variance (ANOVA) with an $\alpha = 0.05$. The primary variables included the binder types (control, SBS-modified, 10% and 15% rubber modified binders), the compaction temperatures (116, 135, 154 and 173°C), and the compaction levels (20, 40, 60, 80, and 100 gyrations).

RESULTS AND DISCUSSIONS

Superpave Mix Design

Table 4 shows the optimum asphalt content (OAC), maximum specific gravity (MSG), bulk specific gravity (BSG), and other related data of the mix designs with four different binders. The optimum asphalt contents of control, SBS-modified, 10% and 15% rubber modified binders were found to be 4.6, 4.7, 6.0 and 6.2%, respectively. Previous research has indicated that, in general, the OAC for the CRM mixtures is approximately 1% higher than that obtained for mixtures made without CRM. The higher OAC for mixtures using the CRM binder is attributed to the thicker film of the CRM binder coating the aggregates due to the presence of the rubber particles (Shen et al. 2006).

Volumetric properties as a function of compaction temperature in SGC

The air void contents of 160 specimens fabricated at four compaction temperatures were calculated. Figure 3 shows the air void contents of the specimens as a function of the compaction temperature. In general, specimens made with control or SBS-modified binders had almost the same air void content over a very wide range of compaction temperatures (116 to 173°C). This means that it is possible to satisfy the two target air void contents of 7±1% and 4±1% using 30 and 70 gyrations; respectively, at all compaction temperatures used in this study. However, in the case of CRM mixtures, the air void contents significantly decreased with an increase in the compaction temperature. The range of compaction temperatures to satisfy both the target air void contents of 7±1% and 4±1% was 140 to 166°C and 154 to 160°C for 10% and 15% rubber-modified mixtures, respectively.

Using one-way analysis of variance, the statistical significance of the change in the air voids with the increase in compaction temperature was examined and the results are shown in Table 5. The data indicates that air void contents of the CRM mixtures are affected significantly by the compaction temperature. Similar to the previous research (Azari et al. 2003, Bahia 2000, Stuart 2000), there was no significant difference, at $\alpha=0.05$ level, among the air void contents of four compaction temperatures within both control and SBS-modified mixtures. Also, the difference of air void contents between control and SBS-modified mixtures was statistically insignificant in most cases, especially at the 70 gyration level.

Figures 4 and 5 depict the change of %VFA and %VMA of the specimens with an increase in the compaction temperature from 116°C to 173°C, respectively. Similar to the air void contents, as expected the %VFA and %VMA of specimens produced with control or SBS-modified binders were found to be almost the same values over the four compaction temperatures. In case of the two CRM mixtures, the general trends of %VFA and %VMA were also similar to the change in the air void contents of the CRM mixtures. However, it should be mentioned that %VMA values of the CRM mixtures were relatively higher than those of the control and SBS-modified mixtures, which had the same air void contents. This is probably due to the higher optimum asphalt contents of the two CRM mixtures; therefore, increasing the effective asphalt contents of the mixtures.

Volumetric properties as a function of compaction level in SGC

The air void contents of 100 specimens manufactured at five compaction levels were calculated. Figure 6 shows the air void contents of the specimens as a function of the compaction level. The general trend observed was that the air void contents decreased, as expected, as the gyration levels increased from 20 to 100 gyrations. Two CRM mixtures, especially 15% rubber-modified, showed relatively higher air void contents at low gyration levels such as 20 and 40 gyrations, and the air void difference between CRM mixtures and control (or SBS-modified) mixtures decreased as the gyration level increased. For instance, the average air void contents at 100 gyrations were 4.3, 3.8, 3.9, and 4.4% for control, SBS-modified, 10% rubber-modified, and 15% rubber-modified mixtures, respectively.

Table 6 shows the statistical significance of the change in the air void contents with increasing the compaction level. In general, the air void contents of each mixture were affected significantly by the five compaction levels used in this study. However, the difference of air void contents between 60 and 80 gyrations was not significant at the 5% level. The only exception was the samples made with SBS-modified binder. In addition, the air void contents of all four mixtures fabricated at 100 gyrations were statistically insignificant at 5% level. When compared to the compaction temperatures, the compaction levels are considered to be a more important factor influencing the volumetric properties of the mixtures, including the two CRM mixtures used and tested in this study.

Rutting properties as a function of air void contents

Figure 7 shows the relationship between the deformation and the repeated load cycles for the four mixtures which were compacted at air void contents of 4±0.5%. From the APA test results, the deformation values after 8,000 cycles of loading were found to be 5.7, 3.7, 4.0, and 3.9 mm for the control, SBS-modified, 10% rubber modified, and 15% rubber modified mixtures, respectively. All of the rut depths are significantly below 8 mm, the recommended value (NCHRP Report 508 2003). The difference of rutting values is thought to be attributed to different binder properties of four mixtures at a test temperature of 64°C, provided that all mixtures used the same gradation of aggregate.

The change in final rut depth as a function of air void contents is shown in Figure 8. In this study, the specimens manufactured using four compaction temperatures and two gyration levels were used to conduct the APA test. As shown in Figure 3, the air void contents of control and SBS-modified mixtures ranged from 4 to 8%, largely depending on the gyration level. With respect to 15% rubber-modified mixture, the air void contents were from 2 to 11%. From the APA test results, the higher air void content in CRM mixtures, as expected, seemed to lead to an increase in the final rut depth. However, it was quite difficult to find a general relationship between the air void content and the final rut depth for each mixture, especially for control and SBS-modified mixtures. To evaluate the rutting properties of mixtures depending on compaction conditions, it is suggested that more research need to be done, increasing the number of samples, using more aggregate and binder sources, and using various compaction conditions.

SUMMARY AND CONCLUSIONS

To investigate the properties of CRM asphalt mixtures as a function of compaction conditions, two CRM binders were incorporated into HMA mixtures designed with one aggregate source and two rubber contents. Two mixtures were made with control binder (PG 64-22) and 3% SBS-modified binder (PG 76-22), using the same aggregate source and gradation, and used for comparison purposes. The CRM binders were produced using one base binder (PG 64-22) with 10% or 15% ambient CRM (-40 mesh) by weight of the binder. A total of 260 specimens were fabricated using the Superpave gyratory compactor at four compaction temperatures of 116, 135, 154, and 173°C, and five compaction levels of 20, 40, 60, 80, and 100 gyrations. The volumetric properties of the mixtures were measured, and rutting properties of those mixtures with different air void contents were evaluated using the APA tests. From these test results, the following conclusions were drawn:

1) The optimum asphalt contents of the CRM mixtures were approximately 1.5% higher than the control mixture, depending on the rubber content used.

2) For the specimens compacted using the Superpave gyratory compactor, the difference in the air void contents as a function of the compaction temperatures was found to be statistically insignificant for the control and SBS-modified mixtures at the 5% level. The specimens had the same volumetric properties at a very wide range of compaction temperatures from 116 to 173°C.
3) The air void contents of the mixtures with CRM binders decreased as the compaction temperature increased from one temperature to the next consecutive temperature. From statistical analysis, it was shown that the compaction temperature significantly affected the total air void contents of the mixtures.
4) Due to the higher asphalt contents of CRM mixtures, the %VMA values of the two CRM mixtures were found to be higher than those of the control and SBS-modified mixtures, which had the same air void contents.
5) The two CRM mixtures showed relatively higher air void contents at low compaction levels, and the difference in the air void contents between the CRM mixtures and the control or SBS-modified mixtures decreased as the compaction level increased.
6) The air void contents of each mixture were influenced significantly by the compaction levels used, but the difference of air void contents between 60 and 80 gyrations was insignificant, with exception of the SBS-modified mixture.
7) The rut depths of the mixtures at air void contents of 4±0.5% were much smaller than the requirement set forth by the South Carolina DOT. The different rutting values were considered to be attributed to different binder properties of the mixtures.
8) The total rut depths, measured by the APA, were found to increase with an increase in the air void contents of the CRM mixtures, as expected. However, it was not possible to suggest a general relationship between the volumetric properties and the rutting

properties of each mixture with this limited data, and more research regarding this issue is needed.

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Figure 7. APA test results for four mixtures with 4 ± 0.5% air void contents.

Figure 8. Change in rut depth as a function of air void contents.

Table 1. The gradation of crumb rubber used in this study

Sieve No. (μm)	Ambient CRM	
	% Retained	% Cumulative Retained
30 (600)	0	0
40 (425)	9.0	9.0
50 (300)	31.9	40.9
80 (180)	32.9	73.8
100 (150)	7.6	81.4
200 (75)	18.6	100.0

Table 2. Properties of four binders

Aging states	Test properties	Control PG 64-22	SBS-modified PG 76-22	10% rubber * modified	15% rubber * modified
Unaged binder	Viscosity @135^{o}C (Pa-s)	0.430	1.475	1.226	2.308
	G*/sin δ @64 ^{o}C (kPa)	1.279	-	2.974	-
	G*/sin δ @76 ^{o}C (kPa)	-	1.338	0.742	1.294
RTFO aged residue	G*/sin δ @64 ^{o}C (kPa)	2.810	-	-	-
	G*/sin δ @76 ^{o}C (kPa)	-	2.508	2.060	2.990
RTFO + PAV aged residue	G*sin δ @25 ^{o}C (kPa)	4074	-	-	-
	G*sin δ@31 ^{o}C (kPa)	-	2129	4480	4112
	Stiffness @-12 ^{o}C (MPa)	217	212	243	225
	m-value @-12 ^{o}C	0.307	0.310	0.330	0.331

* DSR: with the plate gap adjusted to 2 mm. The plate gap adjustment was used to eliminate the influence of rubber particle size.

Table 3. Properties of aggregate

Properties	Standard method	Aggregate
Apparent specific gravity	AASHTO T 85	2.70
Absorption	AASHTO T 85	0.6
LA abrasion	AASHTO T 96	52.0
Soundness	AASHTO T 104	1.6

Table 4. Results of Superpave mix designs.

Property	Mixtures			
	Control	SBS-modified	10% rubber modified	15% rubber modified
OAC (%)	4.6	4.7	6.0	6.2
MSG	2.438	2.433	2.387	2.375
BSG	2.331	2.336	2.291	2.269
%Air void	4.0	4.0	4.0	4.0
%VMA	15.2	15.1	19.4	19.9
%VFA	71.5	72.5	73.4	73.1

OAC: Optimum Asphalt Content, MSG: Maximum Specific Gravity, BSG: Bulk Specific Gravity

Table 5. Statistical analysis results of %air voids of specimens fabricated at different compaction temperatures (α = 0.05)

30 gyrations		Control				SBS-modified				10% rubber modified				15% rubber modified			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Control	1	-	N	N	N	N	N	N	N	S	S	S	S	S	S	S	S
	2		-	N	N	N	N	N	N	S	S	S	S	S	S	S	S
	3			-	N	S	S	N	N	S	S	N	S	S	S	S	S
	4				-	S	S	N	N	S	S	N	S	S	S	S	S
SBS-modified	1					-	N	N	N	S	S	S	S	S	S	S	S
	2						-	N	N	S	S	S	S	S	S	S	S
	3							-	N	S	S	S	S	S	S	S	S
	4								-	S	S	S	S	S	S	S	S
10% rubber modified	1									-	S	S	S	N	N	N	S
	2										-	N	S	S	S	S	S
	3											-	S	S	S	S	S
	4												-	S	S	S	N
15% rubber modified	1													-	N	S	S
	2														-	N	S
	3															-	S
	4																-

70 gyrations		Control				SBS-modified				10% rubber modified				15% rubber modified			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Control	1	-	N	N	N	N	N	N	N	S	S	S	N	S	S	S	S
	2		-	N	N	N	N	N	N	S	S	S	S	S	S	S	S
	3			-	N	S	N	N	N	S	N	N	S	S	S	S	S
	4				-	N	N	N	N	S	S	S	S	S	S	S	S
SBS-modified	1					-	N	N	N	S	S	S	N	S	S	S	S
	2						-	N	N	S	S	S	N	S	S	S	S
	3							-	N	S	S	S	S	S	S	S	S
	4								-	S	S	S	N	S	S	S	S
10% rubber modified	1									-	S	S	S	S	N	N	S
	2										-	N	S	S	S	N	S
	3											-	S	S	S	N	S
	4												-	S	S	S	S
15% rubber modified	1													-	N	S	S
	2														-	S	S
	3															-	S
	4																-

Compaction temperature 1: 116 °C 2: 135 °C 3: 154 °C 4: 173 °C.
N: non-significant, S: significant

Table 6. Statistical analysis results for %air void contents of specimens fabricated at different compaction levels ($\alpha = 0.05$).

Compaction temperature of 154°C		Control					SBS-modified					10% rubber modified					15% rubber modified				
		a	b	c	d	e	a	b	c	d	e	a	b	c	d	e	a	b	c	d	e
Control	a	-	S	S	S	S	S	S	S	S	S	S	N	S	S	S	S	N	S	S	S
	b		-	S	S	S	N	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	c			-	N	S	S	S	S	S	S	S	S	N	S	S	S	S	N	N	S
	d				-	S	S	S	N	S	S	S	S	N	N	S	S	S	N	N	S
	e					-	S	S	S	N	N	S	S	S	S	N	S	S	S	S	N
SBS-modified	a						-	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	b							-	S	S	S	S	S	S	S	S	S	S	N	N	S
	c								-	S	S	S	S	N	N	S	S	S	S	S	S
	d									-	S	S	S	S	S	S	S	S	S	S	N
	e										-	S	S	S	S	N	S	S	S	S	N
10% rubber modified	a											-	S	S	S	S	S	S	S	S	S
	b												-	S	S	S	S	N	S	S	S
	c													-	N	S	S	S	N	N	S
	d														-	S	S	S	S	S	S
	e															-	S	S	S	S	N
15% rubber modified	a																-	S	S	S	S
	b																	-	S	S	S
	c																		-	N	S
	d																			-	S
	e																				-

Compaction level a: 20 gyrations b: 40 c: 60 d: 80 e: 100.
N: non-significant, S: significant

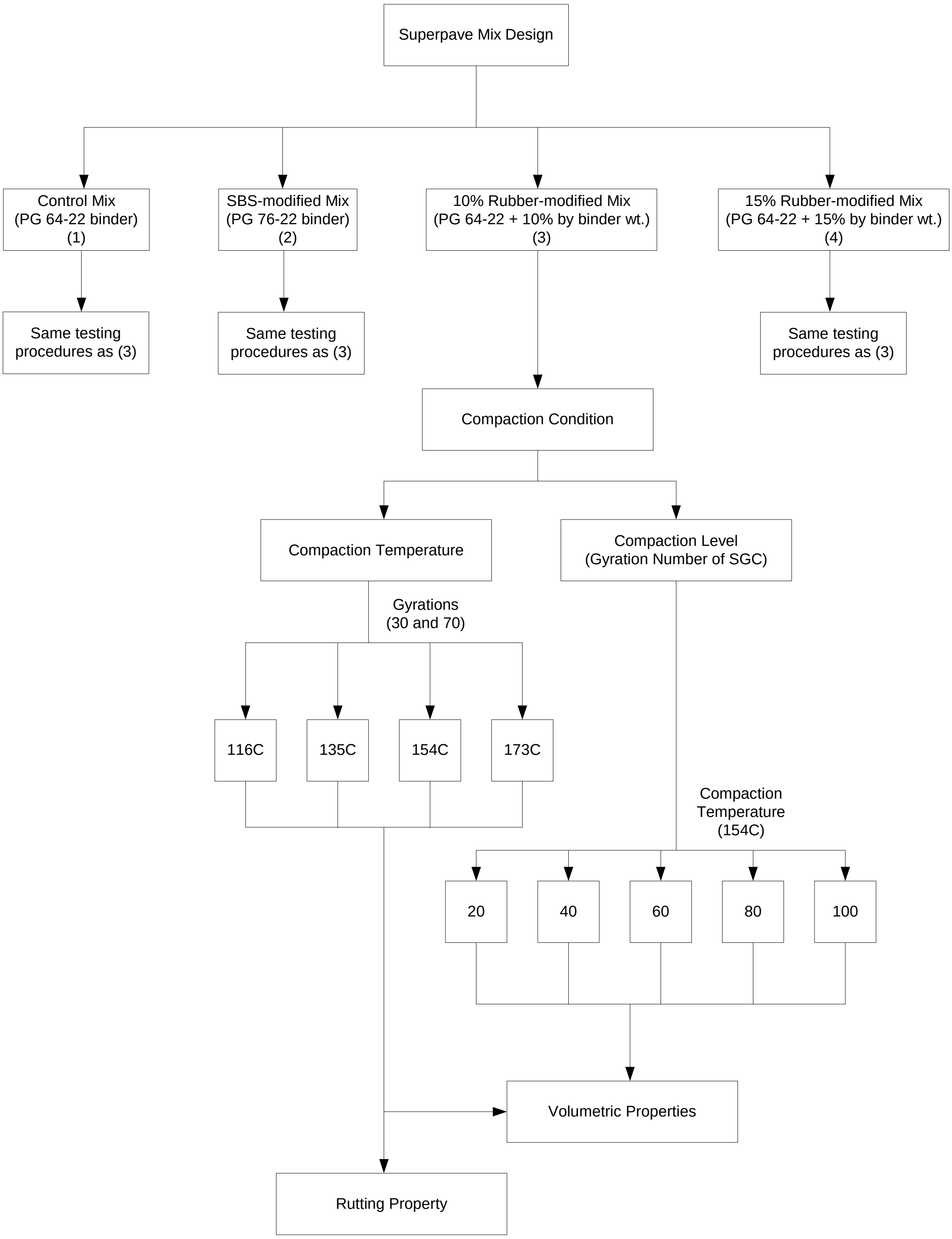


Fig. 1. Flow chart of experimental design procedures.

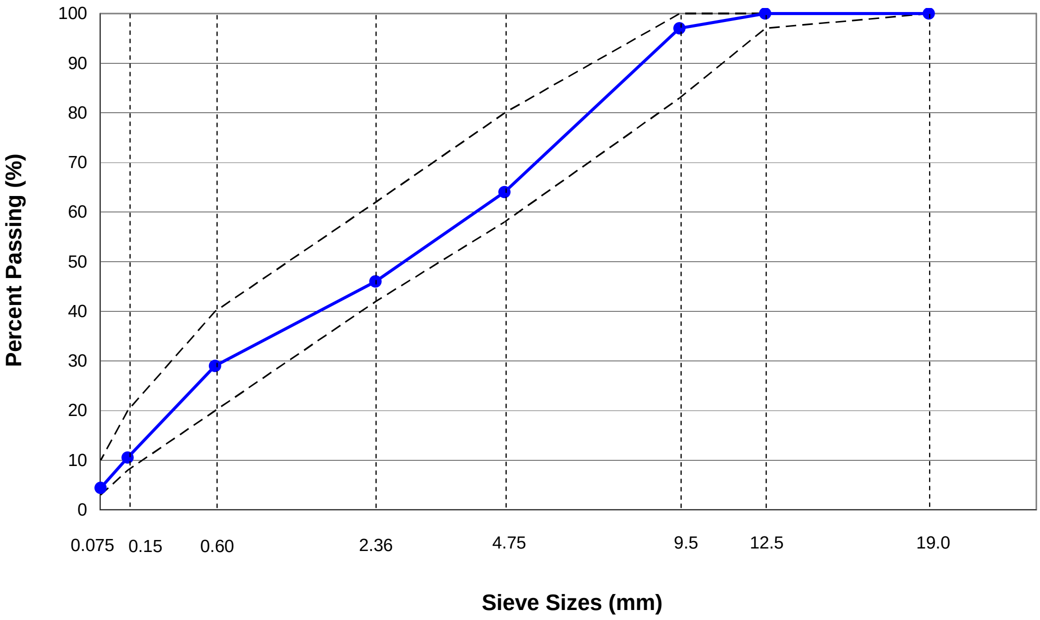
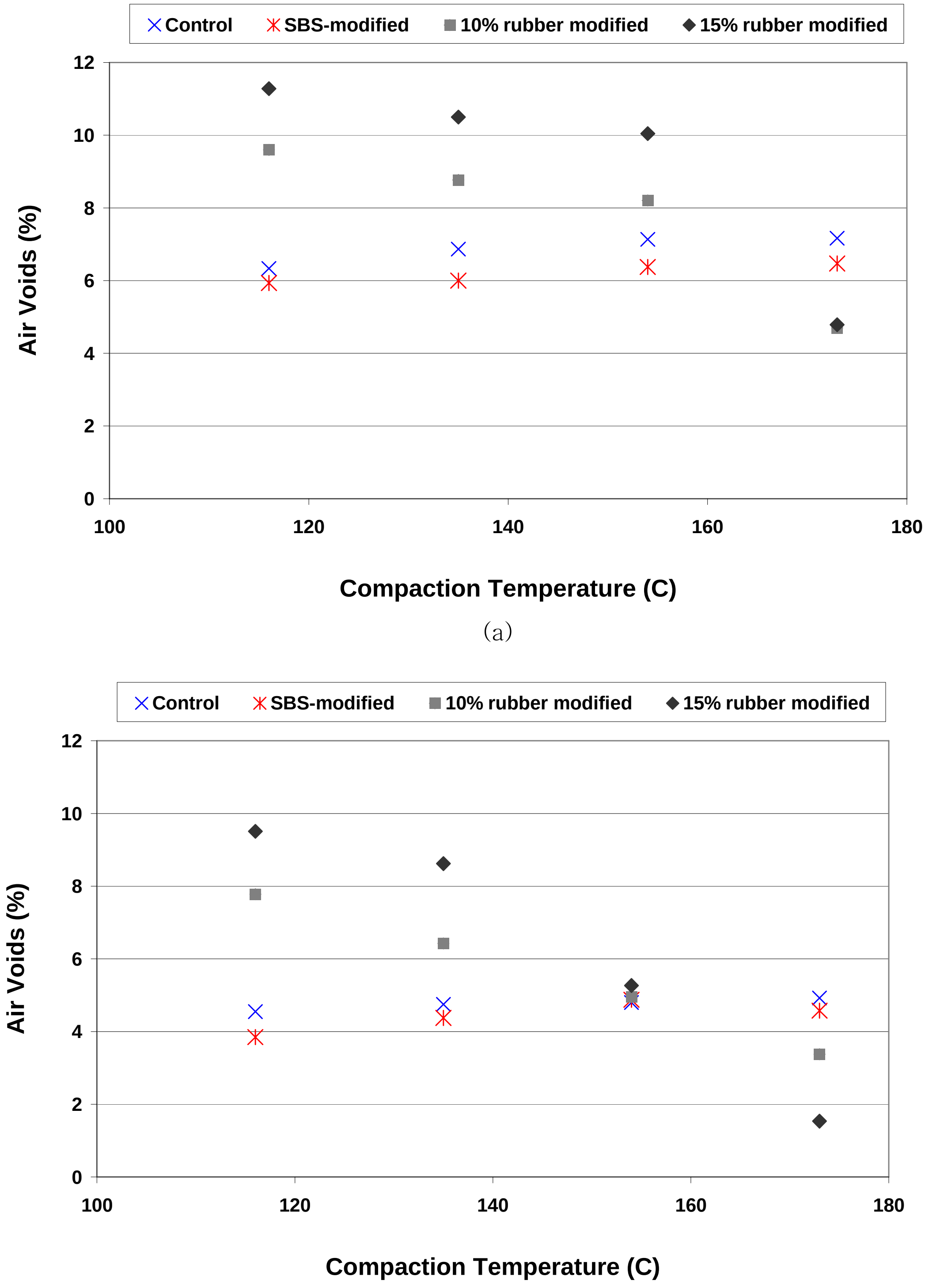


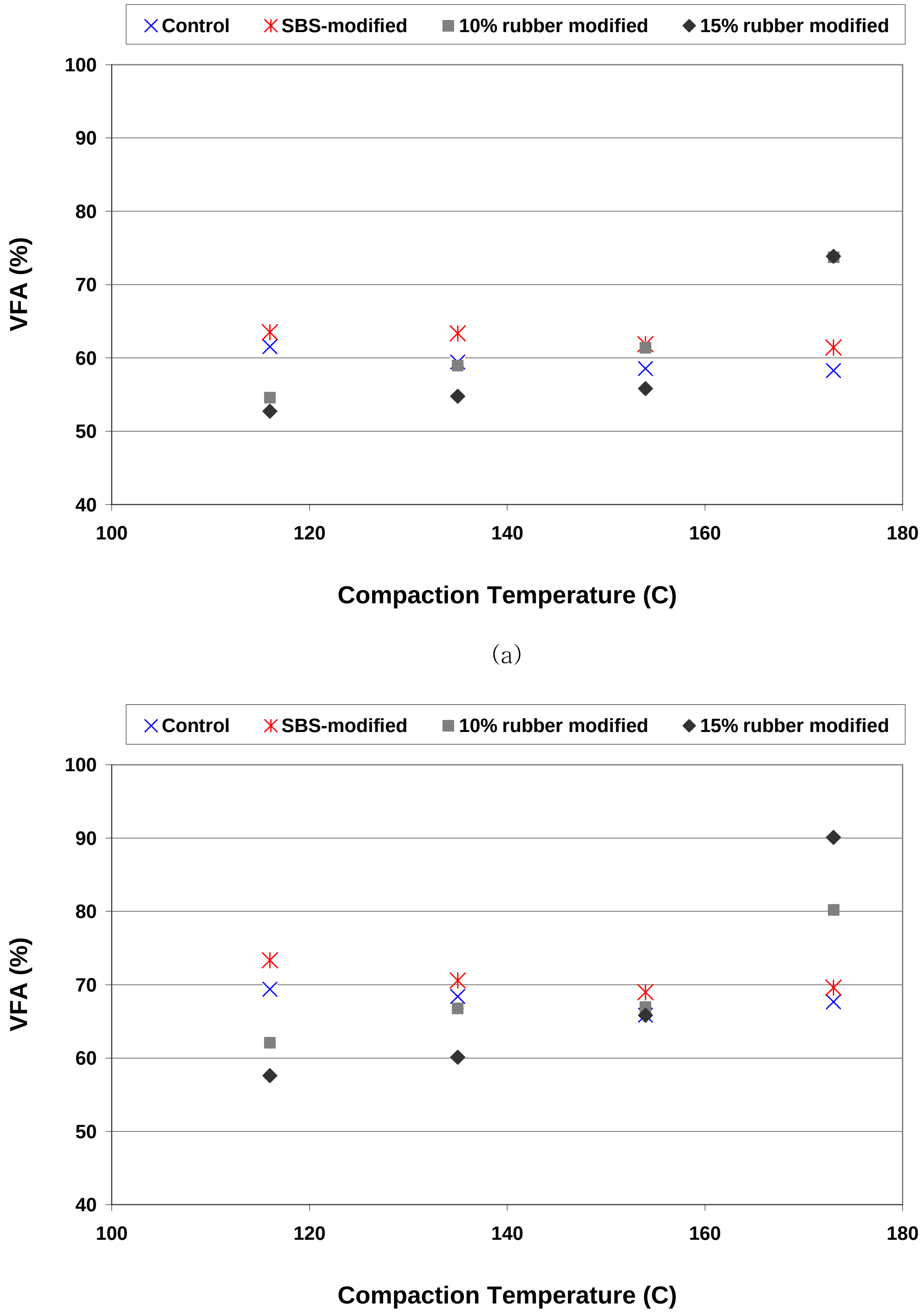
Fig. 2. Gradation chart of 9.5mm mixture.



(a)

(b)

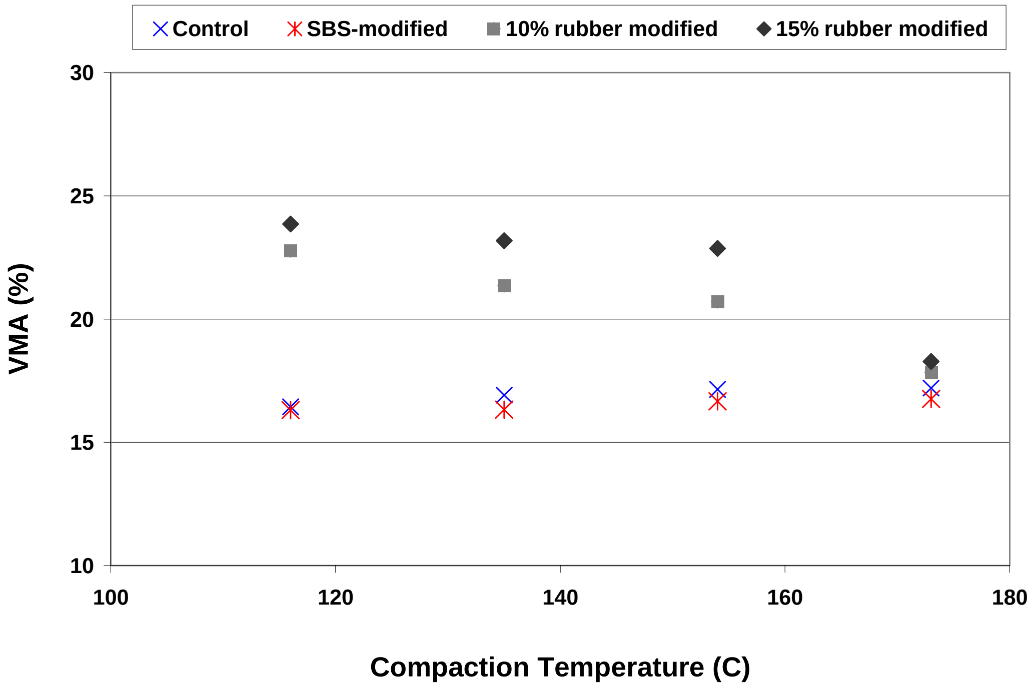
Fig. 3. Change in %air voids as a function of compaction temperature with (a) 30 gyration level and (b) 70 gyration level of SGC.



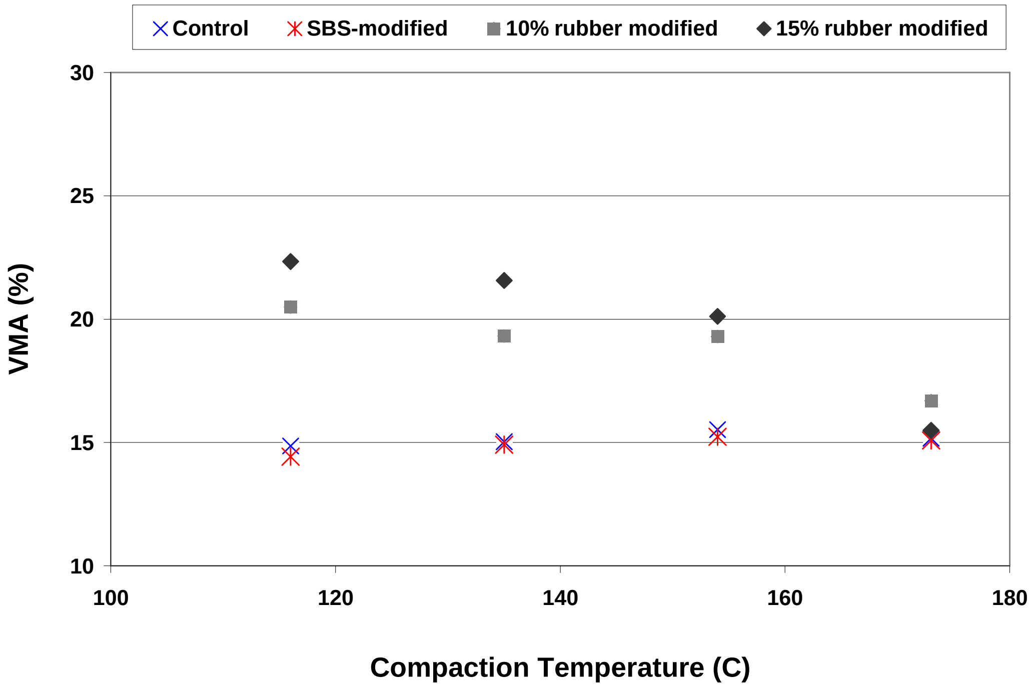
(a)

(b)

Fig. 4. Change in %VFA as a function of compaction temperature with (a) 30 gyration level and (b) 70 gyration level of SGC.



(a)



(b)

Fig. 5. Change in %VMA as a function of compaction temperature with (a) 30 gyration level and (b) 70 gyration level of SGC.

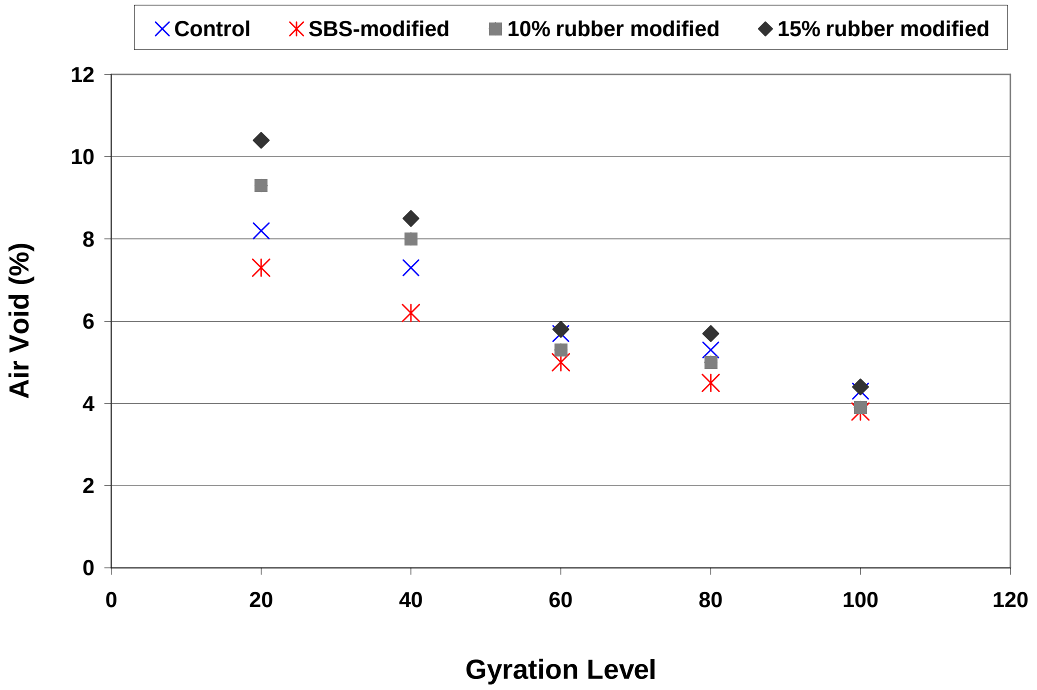


Fig. 6. Change in air voids as a function of gyration level in SGC (at compaction temperature of 154°C).

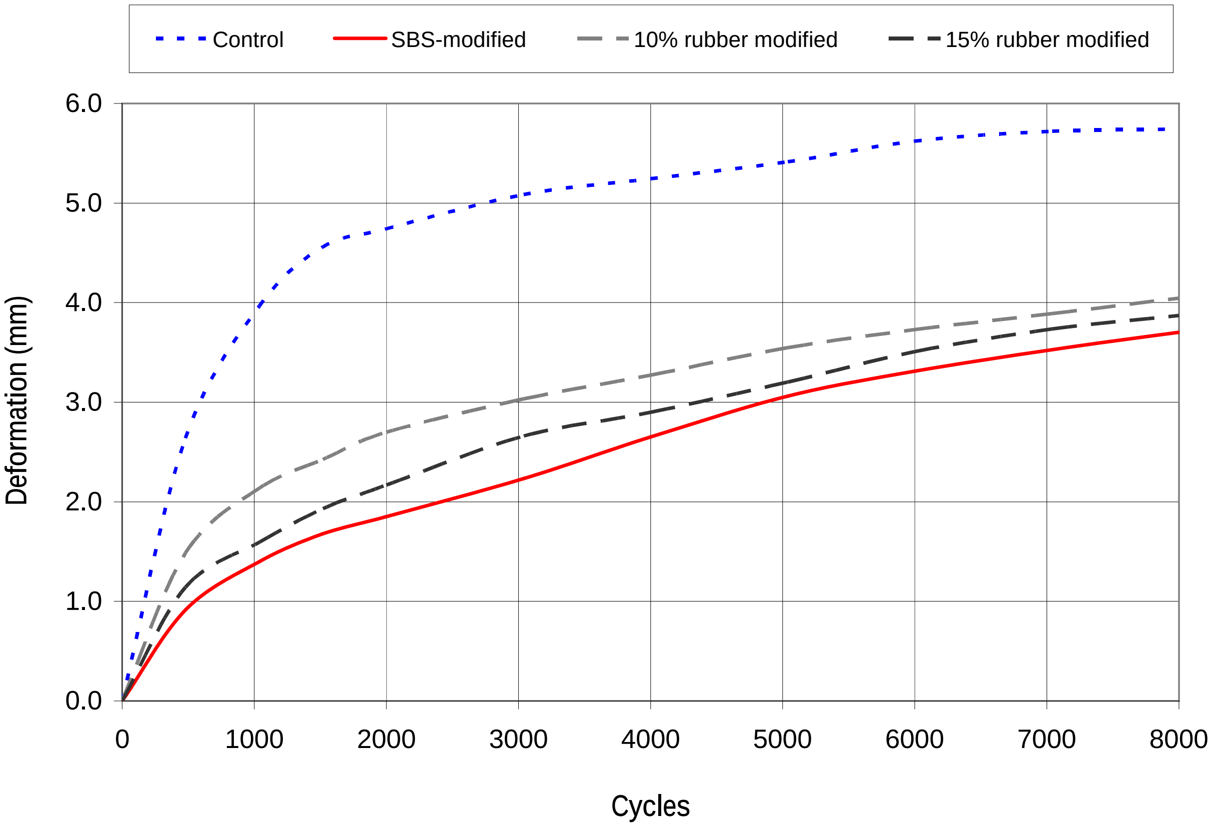


Fig. 7. APA test results for four mixtures with 4 ± 0.5% air void contents.

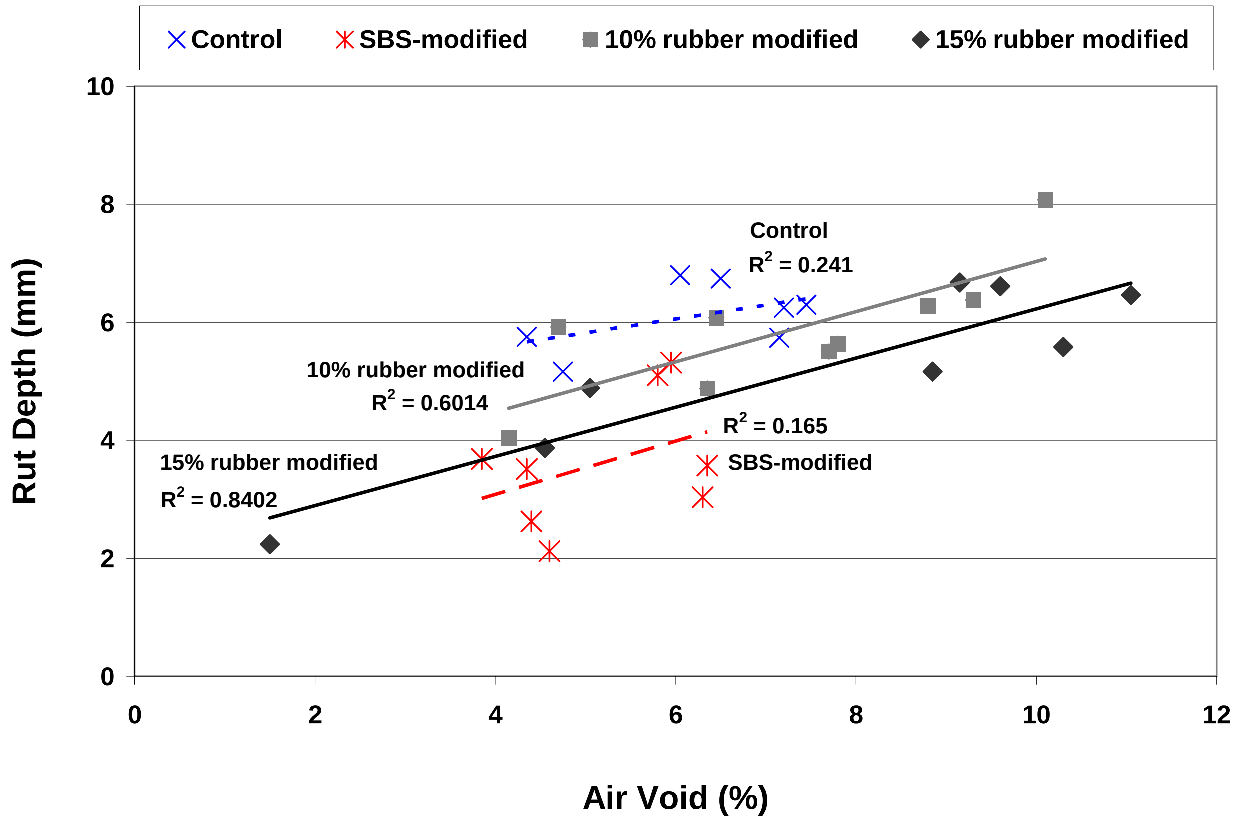


Fig. 8. Change in rut depth as a function of air void contents.